

Bird's-Eye View

Remote sensing of plant, soil, and water ecologies

Clarifies

can yield important information about recent and

Research on

historical events and conditions.

the Ground



OUT in the backyard garden or in the wilderness, we've all seen how plants react to changes in environment. Too little water, too much sun, not enough nutrients, and normally green leaves wilt and turn yellow, evergreens shed their needles, grasses droop and die, new species of weeds and trees replace other plants that are struggling. In these and other ways, plants can provide valuable clues—some obvious, some subtle—about what's going on in their immediate world. Clues that, if interpreted correctly and combined with other information about an area's geology and ecology, can speak to scientists about the past and present and even give hints about the future.

Past events such as clandestine underground nuclear tests or surface digging that occurred many years ago could be revealed. Present events such as methane gas leaking from an underground pipeline, carbon dioxide leaking from geothermal formations, or chemical run-off in streams and estuaries could be pointed out. Future events such as impending landslides could be signaled. All these and more

are reflected in the health and species mix of plants in the area.

Lawrence Livermore sensor physicist Bill Pickles first began noticing what plants can reveal after an underground test at the Nevada Test Site nearly a decade ago. (See the [box on p. 14](#).) Since then, he has joined forces with researchers at the National Aeronautics and Space Administration (NASA), the University of California at Santa Cruz (UCSC), the University of Nevada at Reno, the University of Utah, and Pacific Gas and Electric's (PG&E's) Technical and Ecological Services (TES) Laboratory to explore and develop applications of geobotanical remote sensing. Their collaborations use multispectral imagery and airborne imaging spectroscopy, or hyperspectral imagery, to combine observed plant health and species mixes with soil and mineral distributions. They correlate these distributions to events both natural and human made. Such "translations" of the language of plants, soils, and water are contributing to Livermore's homeland security and energy resource development missions

as well as providing insights into complex ecological systems such as coral reefs and wetlands.

Getting Details on the Big Picture

Geobotanical remote sensing uses both plants and geology to understand a region of interest; it gathers information with systems carried by either airplanes or satellites. Using remote sensors to map aspects of Earth's geology and biological ecosystems is not new. What is new about Livermore's Geobotanical Remote Sensing Program is that it combines commercial and national remote sensing systems of extremely high spatial and spectral resolution with an interdisciplinary methodology. As a result, it has brought together experts in many fields, including remote sensing technology, biology, botany, marine science, geology, ecology, and geothermal research. The team works together to produce an integrated interpretation of what is seen in the imagery and verified on the ground during field trips.

According to Pickles, today's commercial and NASA airborne sensor systems can record 50, 120, 256, and



even more bands in the visible and near-infrared wavelengths with spatial resolutions between 0.5 and 4 meters. Sensors with such a high number of spectral bands are referred to as hyperspectral. Commercial satellites have comparable pixel resolutions, but only image four bands over the same bandwidths. This low number of spectral bands is referred to as multispectral. High spatial resolution of a meter or so is essential for geobotanical analyses, he notes. With a hyperspectral scanner and 0.5- to 4-meter resolution, the spectra from rocks, soils, bushes, and trees aren't heavily averaged together in one pixel of the image but remain somewhat

separate, or are only partially mixed. From hyperspectral data of this quality, researchers can obtain details such as determining the species of individual plants, identifying the locations of mineral outcrops, classifying clumps of plants, mapping unique soil types, detecting water conditions, differentiating road types, and exposing traces of disturbed earth.

Satellite multispectral imagery allows a broad overview of landscapes of interest. Once an area has been identified for further study, a plane carrying a spectroscopic system flies at a predetermined altitude, about 300 to 1,500 meters above ground elevation, gathering data for swaths usually

1 kilometer wide and tens of kilometers long in an overlapping pattern. Data are gathered in narrow, prescribed bands in the visible and infrared spectra. The spatial resolution of the data is usually detailed enough to pick out individual plants on the ground.

These data are processed by researchers using commercial image processing software such as ENVI or Imagine. "We're fortunate that many years of work by many remote sensing researchers has produced advanced suites of sophisticated image analysis software," says Pickles. "This software allows us to focus on analyzing the images and not on developing the computer codes. After all, the focus

Serendipity Leads to Sensing Technique

In the predawn light of September 23, 1993, Livermore physicist Bill Pickles drove his jeep onto Rainier Mesa on the northern part of the Nevada Test Site. He was looking for any changes that might be visual signatures of the 1-kiloton chemical explosion set off in a tunnel under the mesa 24 hours earlier. The shot, made during the international Nonproliferation Experiment, had representatives from many countries present.

The point of the experiment was to see whether underground nuclear explosions could be detected, located, and distinguished from other seismic events such as earthquakes, mine collapses, or large chemical explosions routinely used in mining, quarrying, and civil engineering projects. "It was a worldwide seismic party," remembers Pickles, who was trying to see if remote sensing could be used to pinpoint the location of a clandestine small underground explosion. He decided to piggyback on the event with advanced remote sensing available from the Department of Energy laboratory nearby at Nellis Air Force Base, Las Vegas. Pickles was hoping to find any signatures—such as cracks in the roads, fences knocked over—that might detect an explosion set off in violation of the Comprehensive Test Ban Treaty. At first glance, the visible results had been disappointing. There was no obvious damage to anything on the surface after the underground explosion.

Then 36 hours after the explosion, as dawn broke over the rim of Rainier Mesa, brilliant autumn colors from the surrounding pin oak trees flooded the inside of Pickles's jeep. "I drove into the area for my postshot inspection. I couldn't see anything different at all.

It was very discouraging. So I kept driving and looking around. Something bothered me, tugged at the back of my mind as I drove, but I couldn't put my finger on it."

Two kilometers away from ground zero, it hit him as he gazed out the vehicle window. The pin oak trees surrounding him were green. "The fall colors that had so dazzled me near ground zero were gone! I drove back to ground zero and there, the fall colors were absolutely intense," says Pickles.

The scientific questioning began. Could the shock have precipitated the change to fall colors because it forced the plants into early senescence? Pickles approached National Aeronautics and Space Administration (NASA) botanist Greg Carter with the question. Carter said it was possible. The shock of the ground motion might have forced the plants to shut down their root systems, dehydrating and thus stressing the plants.

Carter had an ongoing NASA program to make spectral measurements of plants that all looked healthy to the naked eye but were in fact under some stress. He was in the process of determining which narrow wavelength bands in the reflected visible spectrum were an indicator of plant stress. "We got the list of his bands," says Pickles, "and found that two of my bands acquired using multispectral imaging just overlapped his bands." (The Livermore bands were 30 and 50 nanometers wide, while Carter's were only 2 nanometers wide.)

Pickles focused on the relevant bands to measure ratios of images before and after the shot. "The larger the ratio, the larger

of our work is on understanding phenomena affecting vegetation and soil, not building applications.”

Researchers use the results of the computer software analysis and their ground observations to produce a wealth of detailed specialized maps. They superimpose and overlap these maps using geographic information systems (GISs), looking for patterns and relationships. For instance, a map of minerals produced by geothermal activity overlaid with a map showing distributions of plant species or plant health could pinpoint the location of a hidden geothermal source. The variety of maps include those of geology, botanical species and distributions,

Members of the geobotanical remote sensing collaboration and the plane with a HyMap hyperspectral sensor on board. The sensor is mounted inside one of the doors and takes data through a hatch in the bottom of the aircraft.

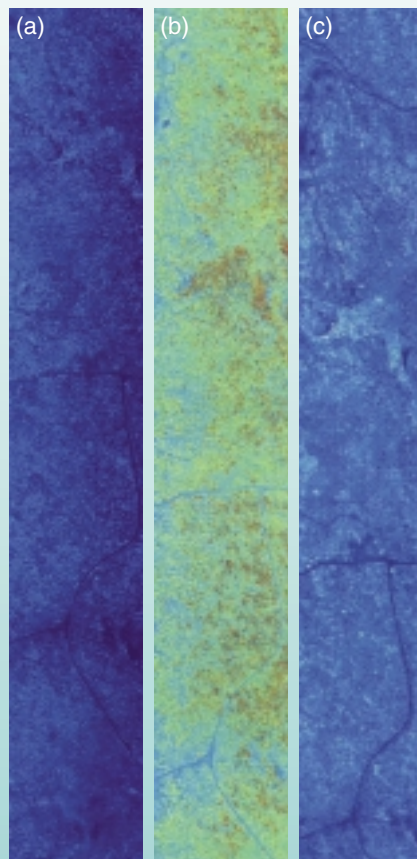


the plant stress,” says Pickles. “A ratio above 3.75 is definitely indicative of plant stress in Carter’s research.” He found a pattern of plants located near ground zero with ratios well above 3.75. This pattern does locate the area above the explosion to within several hundred meters.

It seemed entirely possible that the shock wave from the test’s blast could have temporarily dehydrated the trees. Pickles and Carter tested this hypothesis by shocking trees at a large landscape contractor’s tree-growing area in Calaveras Canyon near Sunol, a few miles from Livermore. To mimic the shock wave produced by the shot, which was known to produce a maximum vertical ground displacement of about 1 meter, a crew of workers hoisted trees growing in large containers to 1 meter above the ground and then dropped them. Using a small, narrowband filtered camera, Pickles and Carter recorded and measured previsual (before it is apparent to the human eye) stress in the trees’ foliage as the plants went into shock. They measured several metabolic parameters for each tree.

The experiments showed the photosynthesis rates of the trees changed by the dropping. This finding was similar to what was seen at Rainier Mesa after the Nonproliferation Experiment. In both instances, the trees slowly recovered in about one week.

“Had the Nonproliferation Experiment occurred but two or three weeks later,” says Pickles, “yellow autumn foliage would have been the norm for pin oaks up on the mesa. It was pure serendipity that the trees were thrown deep enough into senescence at a time when I could actually see the difference.”



Ratio images of stressed vegetation at and around ground zero taken (a) 12 hours before, (b) 12 hours after, and (c) 1 week after the Nonproliferation Experiment shot. The last two images reveal that all the plants went into shock immediately after the shot, after which they recovered at different rates. Plant stress level is indicated by different colors. Blue represents normal or nonstressed, green and yellow are intermediate stressed, and red represents most-stressed plants.

known as well as new and hidden faults, pockets of minerals that have been altered by high temperatures, the effects of carbon dioxide emissions on surface plants, and more.

Pickles works with Don Potts and Eli Silver, professors of biology and geology at UCSC who also head up a doctoral program in geobotanical



A Pacific Gas & Electric worker points to one of the discovered leaks in the exposed pipe.

remote sensing. The program focuses on gathering geological, biological, and ecological data over large areas of interest. Remote sensing techniques are used to create an overall picture of how plants respond to changes in the environment, such as those caused by heat, salinity, contamination, shock waves, and seasons.

Initially, the research program focused on analyzing imagery for plants under shock—to support studies for the Comprehensive Test Ban Treaty—but it has expanded to mapping soil types, soil contamination, plant species, plant health, minerals, water, and water content. The data are used for Livermore's missions in energy technology and homeland security. Geobotanical remote sensing techniques are also being applied to ecological studies in Elkhorn Slough in Monterey, California, and coral reefs in the new North West Hawaiian Islands Coral Reef National Sanctuary. (See the **box on p. 18.**)

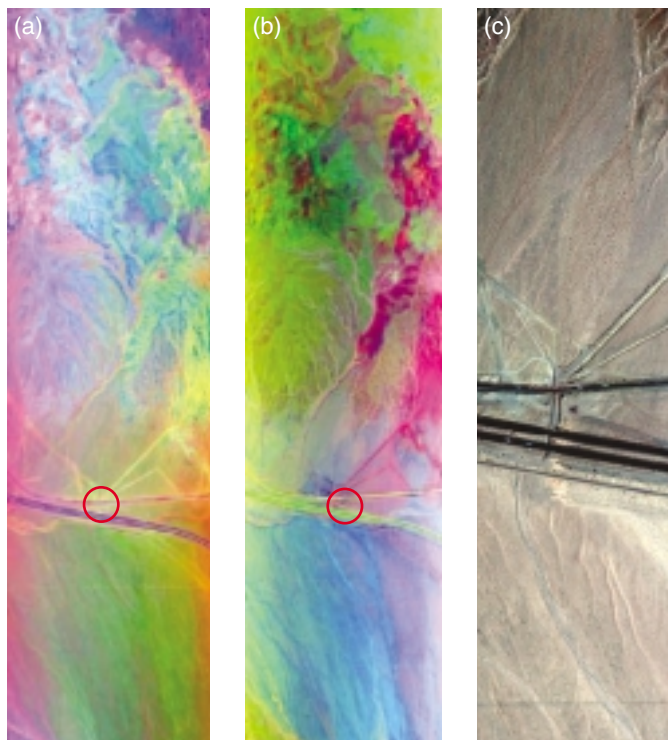
Keeping Pipelines Safe

The Laboratory's Homeland Security Organization is responsible for providing comprehensive solutions for defending against terrorism. As a part of this mission, the Laboratory has been assessing the nation's energy infrastructure, including natural gas utilities. Geobotanical remote sensing is one method being developed to detect hazards to natural gas pipelines. "We are looking for ways to identify leaks, landslides, earthquakes, and third-party incursions—deliberate as well as accidental damage, such as the kind that could happen when fields are plowed too deep, subdivisions are built over pipelines, that sort of thing," says Pickles.

Pickles and Don Price of PG&E's TES Laboratory in San Ramon, California, are collaborating on this pipeline monitoring program. The collaboration, which includes UCSC graduate students, recently completed a pilot project in Cordelia, California, at a PG&E pipeline site in an area where a landslide bent the pipeline. (The bent part has now been bypassed with a new section of pipe.) The pilot project used high-resolution IKONOS satellite multispectral imagery to see if the landslide area could have been detected by remote sensing before it broke loose and damaged the pipe. Results of the project are being applied along other PG&E pipelines to reduce risk and enhance infrastructure reliability.

PG&E is providing instant information about new leak locations, site access, leak area appearance, repair details, and historical site information. When Pickles and Price are informed of a new leak location, they arrange for low-altitude overflights by NASA Jet Propulsion Laboratory, NASA Ames Research Center, or commercial hyperspectral imaging providers such as SpecTIR Corporation or HyVista Corporation. "Geobotanical changes are much more

Three views of a pipeline leak.
(a) Minimum noise fraction (MNF) transformation in pseudo-color, showing leak area west of Ludlow, California. (b) Using different MNF transformed bands emphasizes features differently and is a common technique for sorting out what is seen in the imagery. (c) A true color, three-band image at 3-meter resolution.



sensitive indicators than, for instance, airborne detection of methane in a plume that accumulates over a leak,” says Pickles.

So far, two areas have been successfully imaged. One area is on the main pair of PG&E pipelines that run through the California desert. The leaks there were between the towns of Ludlow and Amboy. The other is in the Sunol Canyon in the San Francisco Bay Area. For the Amboy–Ludlow site, the team had NASA Ames acquire spectroscopic data in 50 spectral bands, including in thermal infrared and infrared portions of the spectrum, in bandwidths of a few nanometers, and at a spatial resolution of 3 meters. They then used the resulting imagery to map species types, plant health within species types, soil types, and soil conditions.

PG&E’s failure analysis showed that the Ludlow and Amboy leaks occurred in the original welds of the pipeline when it was buried nearly 40 years ago. “The area and vegetation has been subject to 40 years of methane leakage,” says Pickles. “You can tell when you go into the Amboy area on foot that there’s something going on. The plants in the vicinity of these leaks look strange.”

In the Sunol leak, the failure was much more recent and of shorter duration. Although only leaking for a few months, the grass above the leak was clearly in stress and looked brown compared with the surrounding vegetation. Pickles and Price are currently analyzing hyperspectral imagery acquired by SpecTIR within three days of the leak being noticed to see if the brown spot is visible in the images.

Pickles says that the technique shows promise for continuous, real-time monitoring of the pipelines. “The detail we pick up can’t be obtained by satellite imagery yet. Basically, our approach provides an alert that something is up, something that

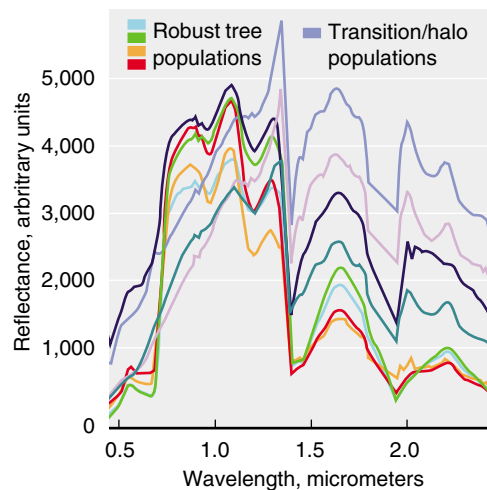
requires a closer look. Where to look is important to utilities like PG&E because in California alone there are some 12,000 miles of transmission gas pipelines to monitor.”

Uncovering Geothermal Sources

Geobotanical remote sensing is also being used to support the DOE mission to discover new hidden geothermal

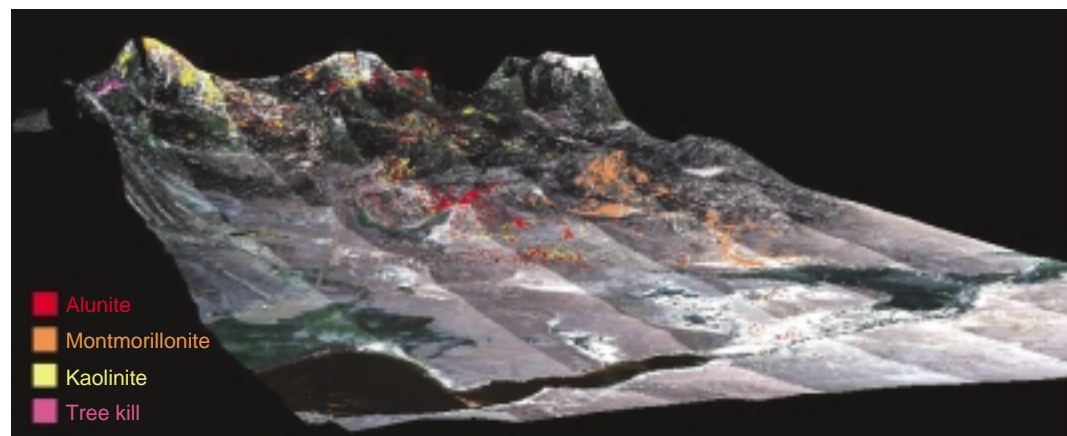
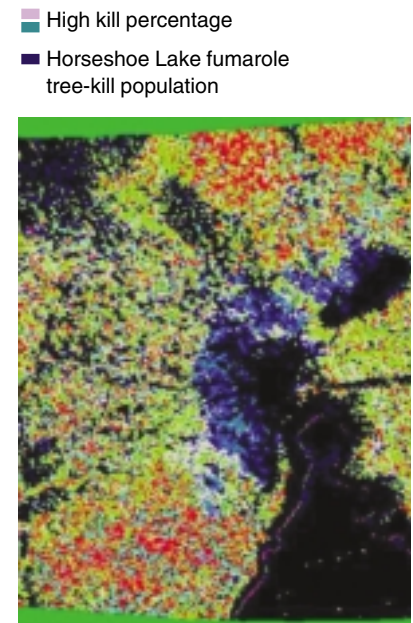
resources that could be used as energy sources. This application got its start in 1996, when Livermore’s geothermal program funded a team that included Pickles, Silver, Potts, and UCSC graduate student Brigette Martini to see if geobotanical remote sensing could identify plants stressed by geothermal activity. “If you hike into a geothermally active area and look

(a)



(a) Spectral signatures of quantitative stages of tree health. These signatures were used to produce (b), a map of tree health in and around the tree-kill area, using the same spectral colors.

(b)



Long Valley Caldera mapped with HyVista 3-meter hyperspectral imagery, showing tree-kill areas and the high-temperature mineralization that marks historical geothermal effluents.

Studying Sensitive Ecological Systems

The techniques developed by Livermore and University of California at Santa Cruz (UCSC) researchers also have potential applications in monitoring and setting baseline conditions for ecologically sensitive areas, such as wetlands and reef systems. UCSC graduate students under professor Don Potts are pursuing these possibilities in two projects that are mapping Elkhorn Slough (a coastal wetland near Monterey, California) and shallow coral reefs off the coast of Hawaii's Oahu Island.

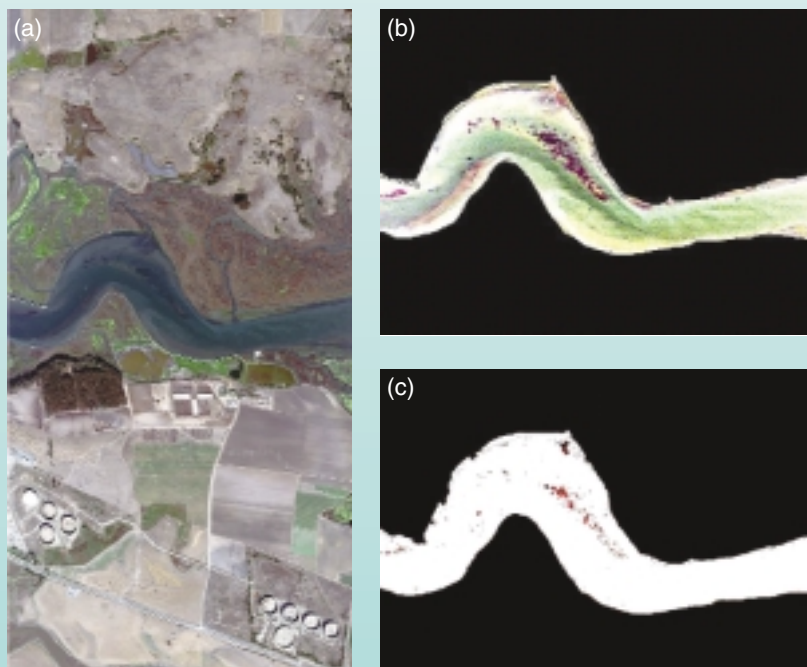
Coastal zones contain some of the most biologically diverse and productive ecosystems on Earth. Over half of the world's current population inhabits these coastal regions, as will much of its expected increase. Along with the human encroachment comes increased environmental impacts and biological stress in coastal and shallow marine ecological systems, stresses that deplete natural resources. Collecting comprehensive data about the extent of resources and impacts and having the ability to

document temporal changes in these areas are essential requirements for successful management and planning.

UCSC researchers are using geobotanical remote sensing techniques to identify and map environmental stress in vegetation found around the terrestrial-aquatic interface of Elkhorn Slough. The home to many species of fish and invertebrates, Elkhorn Slough is also on the migratory path of West Coast birds, and its wetlands provide important nursery and breeding grounds for many animals. UCSC researchers and graduate students are using geobotanical remote sensing techniques to search for patterns of stress in vegetation. Although hyperspectral methods have been used in terrestrial systems for years, there have been fewer applications in coastal and shallow marine systems. UCSC researchers are creating a spectral library for this ecosystem and systematically evaluating different stress indices for use with its estuarine plants as well as evaluating chemical inputs to the

system such as those from pesticides and nutrients. The end result will be maps of vegetation distributions and stress that will provide a tool for sustainable ecosystem planning.

Coral reef ecosystems are also extremely sensitive to changes in their environment—whether those changes are natural or induced by humans. UCSC is using hyperspectral remote sensing to study the coral reef system in Kaneohe Bay, on the northeast coast of Oahu. The reef is subject to constant change, including natural change such as large freshwater flows and the deposition of land-derived sediments and human-driven changes from agriculture, grazing, and the ever-increasing urbanization of the coast. Researchers are using hyperspectral remote sensing data to characterize the organisms that make up the reef, including corals, algae, and invertebrates. The spectral data are being compared with oceanographic and water quality data to look for biological indicators of environmental stress in the spectral response. In particular, UCSC researchers are examining whether spectral signatures can characterize the physiological response of corals to salinity, temperature, dissolved oxygen, and concentration of nutrients, and they are looking for spectral indicators of coral health.



Although hyperspectral methods have been used in terrestrial systems for years, there have been few applications in coastal and shallow marine systems. UCSC graduate students Daria Siciliano and Stacy Jupiter are using geobotanical remote sensing techniques to map eelgrass beds in Elkhorn Slough, looking at vegetation distribution and for signs of stress. These maps and others like them will provide tools for sustainable ecosystem planning. (a) Red-green-blue (RGB) image of the area. (b) Stretched RGB image with the land masked out. (c) The (b) image showing only the eelgrass.

around at the vegetation growing there,” says Pickles, “you’ll see that some of the plants are not doing well. Some species might be struggling. Others—which you’d expect to find in the region—are completely absent, yet other species are flourishing. We wondered if we could go into an area where the geothermal activity isn’t so obvious and check plants for geothermal stress, thereby tracking down geothermal resources.”

The team decided to focus on southern California’s Mammoth Mountain located on the western rim of the much larger Long Valley Caldera—an area well known for its geothermal volatility, with many hot springs and fumaroles. One of three active calderas within the contiguous U.S., Long Valley has witnessed periodic volcanic degassing and increased seismic activity over the past 20 years.

The Horseshoe Lake region located on the southeast flank of Mammoth Mountain was the team’s specific focus. In May 1990, a year after a six-month swarm of earthquakes, dead trees were seen in increasingly large numbers at this site. In 1994, soil gas measurements made by the U.S. Geological Survey (USGS) proved that the trees had been asphyxiated by an enormous quantity of carbon dioxide in the ground. In some cases, up to 90 percent of the gas measured in the soil was carbon dioxide, compared with less than 1-percent concentrations in soils outside the tree-kill areas. Carbon dioxide is outgassed by geothermal systems, and the trees died because of geothermal stress. The tree-kill area was a good place to see if hyperspectral images would corroborate the USGS measurements and be a good detector of geothermal resources.

Martini received her Ph.D. in December 2002 from UCSC. Under advisers Silver and Potts, her thesis was on the Long Valley Caldera and Mammoth Mountain system. As part of the thesis, Martini used low-altitude,

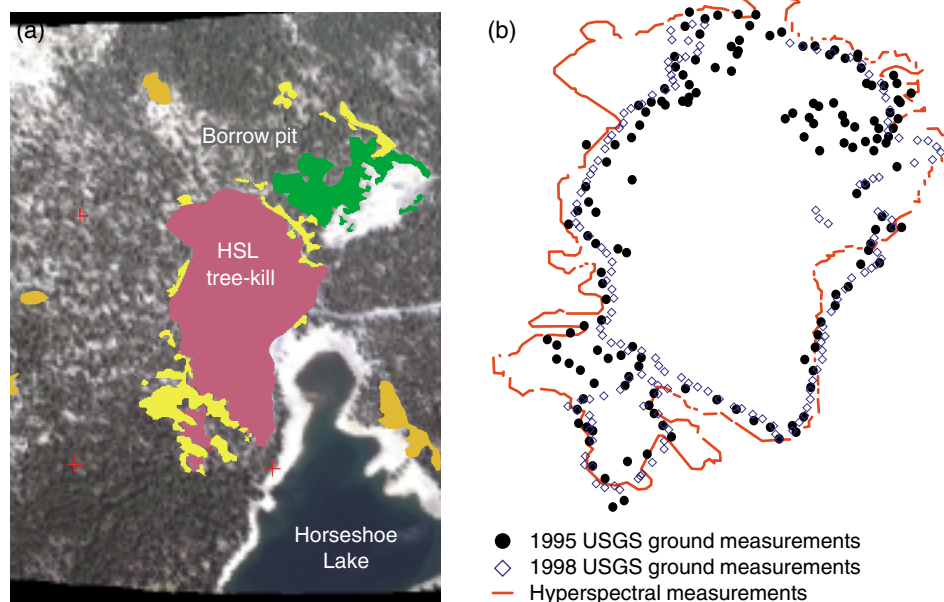
high-resolution hyperspectral imagery to map altered minerals, hidden faults, and the tree-kill areas of Mammoth Mountain. She extracted spectral signatures of healthy robust trees, dead trees, and physiologically stressed trees from the imagery and used it in several mapping schemes. She was able to characterize geothermal activity along the Long Valley fault lines by detecting the release of carbon dioxide and identifying areas where carbon dioxide was coming out of the ground in measureable amounts.

When she compared her mapping of carbon dioxide leakage areas with those measured on the ground by John Rogie of USGS at Menlo Park, the agreement was, notes Pickles, remarkable. Her results show that hyperspectral data can provide accurate geologic and biological information about a geothermal system quickly and without a host of ground-based monitoring

programs. Says Pickles, “Martini showed that when we move away from the center of the tree-kill area, plant health improves as we get further away. She discovered that it was possible to spot carbon dioxide leaks that were not previously mapped.” (For more information about Martini’s work, see www.es.ucsc.edu/~hyperwww/.)

The part of the collaboration dealing with the geothermal exploration project has expanded to include the University of Nevada at Reno and the University of Utah. It is now using geobotanical remote sensing techniques to look for possible new geothermal sites in many places in the western United States.

The expanded collaboration is funded by a DOE program that has the goal of dramatically increasing the use of geothermal energy in the western U.S. To accomplish that goal requires identifying and locating new geothermal fields that could potentially



Plant-stress mapping results at Horseshoe Lake (HSL) using 3-meter hyperspectral imagery.

(a) The Horseshoe Lake tree-kill mapping results. The lightest shades represent transitional zones, while the darker shades show the present boundaries of dead populations.

(b) Hyperspectral-based size estimates of the tree kills compared with contours of average carbon dioxide emissions measured on the ground by the U.S. Geological Survey (USGS) over several years.

be used to produce electric power. In the past, geothermal fields have mostly been discovered by their characteristic surface effluents—springs and fumaroles, for instance.

Most of these fields in the western U.S. are now well catalogued. But questions remain as to whether there are a large number of currently undetected hidden thermal systems, systems that have little outflow to the surface, and whether there are large resources that are untapped in the known fields. Geobotanical remote sensing images in the visible and near-infrared spectra have proved successful in mapping subtle geobotanical surface clues that could lead to such discoveries. Currently, geothermal exploration projects are being conducted with newly acquired hyperspectral imagery of the Dixie Meadows and Fish Lake Valley fields in Nevada.

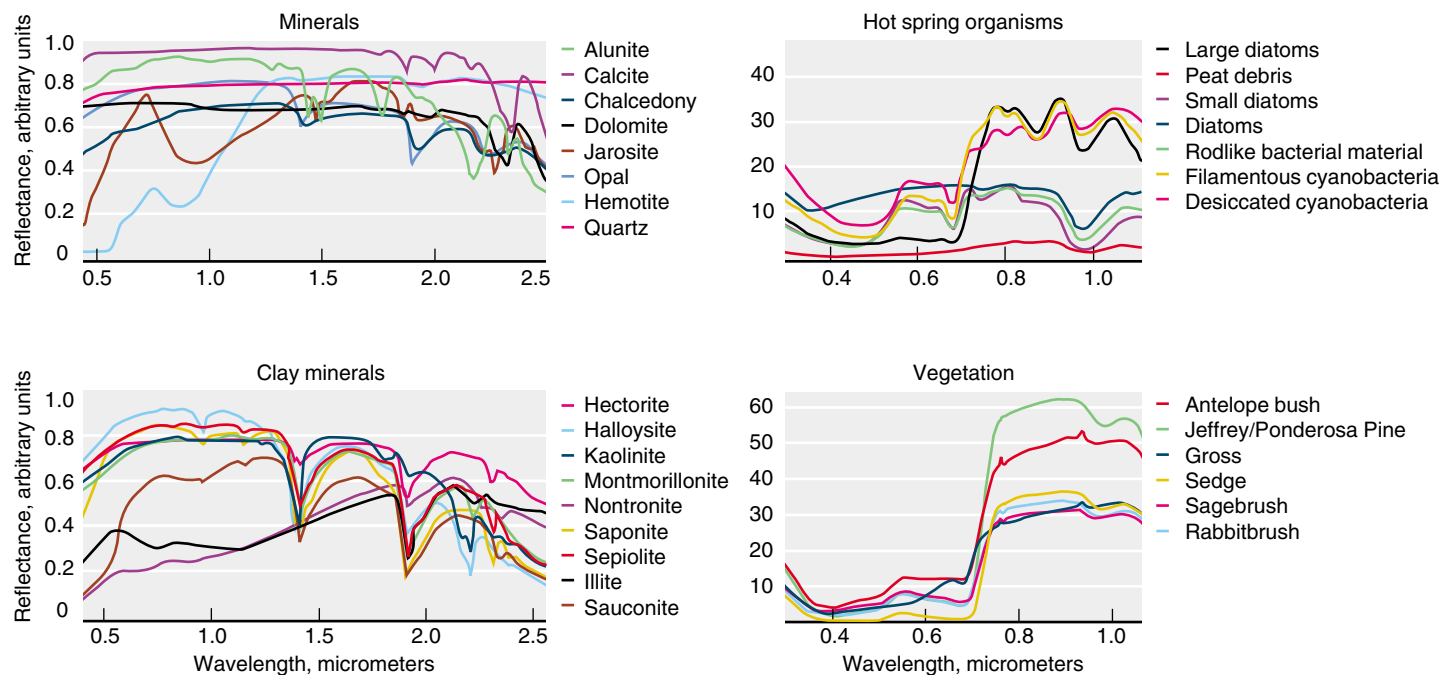
Watching Sequestered Carbon

As fossil fuel burning and tropical deforestation cause more carbon

dioxide to make its way into the atmosphere, the U.S. and other nations are researching strategies to capture excess carbon dioxide and inject it into appropriate underground formations. Once there, it would either remain sequestered from the atmosphere for thousands of years or be available for near-term industrial use. Livermore has been involved in carbon sequestration research in a number of ways, such as developing criteria for identifying subsurface geologic formations that could be used for carbon dioxide storage. (See *S&TR*, December 2000, pp. 20–22.) Livermore's geobotanical remote sensing technique has also emerged as a primary, region-wide, early warning system for detecting carbon dioxide leaking from underground formations where it has been sequestered. Pickles explains, "This was a natural outgrowth of our work on looking for geothermal resources since we also would be monitoring the vegetation on the surface above. But instead of looking for any

plant response to a geothermal resource, we'd be looking for carbon dioxide leaking from a reservoir to the surface."

The Laboratory's geobotanical remote sensing program is contributing to the Storage, Monitoring, and Verification task force for the Carbon Capture Project (CCP), an international effort funded by international energy companies and a number of governments. The goal of the project is to reduce carbon emissions and contribute toward a sustainable, environmentally acceptable, and competitively priced energy supply for the world. Among other efforts, the project is developing technologies to reduce the cost of capturing carbon dioxide from combustion sources and safely store it underground, where it can then be retrieved as needed. As Pickles notes, carbon dioxide has a value. It can be pumped into a geologic formation to promote increased oil flow and enhance oil recovery. Carbon dioxide is also an important industrial component used in making dry ice and in various chemical



Hyperspectral images provide distinctive spectral shapes that allow identification of mineral types, clay soil types, plant species, plant health within species types, and hot and cold spring microorganisms. These spectra are from Mammoth Mountain–Long Valley hyperspectral imagery but are representative of most areas.

processes. (For more about the CCP, go to www.co2captureproject.org/.)

Livermore and UCSC researchers are testing their remote sensing techniques at the Rangely, Colorado, Enhanced Oil Recovery field. They hope to detect and discriminate hidden faults, establish geobotanical baselines, and look for effects of leaking carbon dioxide on plants and microorganisms in soil and water from low-altitude airborne hyperspectral imagery. Armed with on-the-ground carbon dioxide emission maps for plant species at Mammoth Mountain and high-resolution remote imagery of the same area, Martini

established a semiquantitative relationship between plant health and amounts of average carbon dioxide emission. The team then acquired high-spatial-resolution imagery of the Rangely oil field in August 2002 and conducted an on-the-ground study of Rangely in collaboration with Ron Klusman, a professor from the Colorado School of Mines. Pickles and UCSC graduate student Wendy Cover are now analyzing the imagery and beginning to map signatures of carbon dioxide leakage, plant species, and soil types. Preliminary results show some interesting plant and soil signatures.

Pickles, Cover, Potts and Charles Christopher of British Petroleum-America, the CCP manager for this research, will return to the Rangeley field in June to check their interpretation of the imagery analysis, make more carbon dioxide measurements on the ground, and make detailed spectral measurements of special features. The next steps are to produce detailed geobotanical maps and maps of hidden faults, start some continuous carbon dioxide monitoring at potential leak points, and begin connecting surface features to subsurface modeling and existing oil field data.

The goal, says Pickles, is to develop a technique where a leak from an underground carbon dioxide reservoir could be detected quickly and dealt with. "Suppose an earthquake happens, and an underground carbon dioxide reservoir forms a crack. Carbon dioxide would then begin to appear at the surface," Pickles says. "Ideally, we would quickly

see something strange going on in the vegetation above the fractured area. We would have already mapped out hidden faults and know about the earthquake. We would provide the early warning, so that a team could go out into the field, monitor the area, and remediate as necessary. Successful carbon sequestration involves many aspects; we provide the vigilance that will keep it safe."

Focusing at Ground Level

The geobotanical remote sensing program has come a long way and developed in many different directions from its initial beginnings. From providing early warning on pipeline infrastructure to geothermal energy to carbon sequestering and charting delicate ecological systems, the program has thrived on synergy. As remote sensing techniques improve, bringing better spatial and wavelength resolution, field work requirements have been minimized. In the end, it's the unique point of view of the researchers that brings the real power to this program.

"At first, people were skeptical. Being able to sort out events from plant health was just a little hard for some folks to swallow," says Pickles. "But time has proven that high-resolution geobotanical imaging really works. It provides a complete picture and history. If you can learn how to read the signs, nature will tell you everything you need to know."

—Ann Parker

Key Words: carbon sequestration, Elkhorn Slough, energy infrastructure, geobotanical remote sensing, geothermal energy, homeland security, Mammoth Mountain, Nonproliferation Experiment.

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(a) One line of hyperspectral imagery of the town of Rangely, Colorado. This image is shown (b) closer and (c) even closer. Note in (c) that the resolution is good enough to see cars on Main Street. The imagery is useful for learning how to prepare geobotanical maps of carbon dioxide leakage under towns.